2 MINERνA Physics Goals and Detector Design Drivers

2.2 Resonant Pion Production

2.2.1 Introduction

The production and decay of nucleon resonances in neutrino interactions is a significant part of the total neutrino cross section in the few GeV region. These resonances have been explored using electron scattering experiments, but different form factors contribute in the neutrino case, and simulations rely on an early theoretical model by Rein and Sehgal [1]. Because the structure of the model is not as simple as either quasi-elastic or deep inelastic scattering, and because existing neutrino data does not provide significant constraint, there are large uncertainties on the contribution to the total cross section value and its shape.

Resonance production is the least certain part of the neutrino cross section picture, yet it may be the most important. Current and recent neutrino programs (K2K, MiniBoone and MINOS) and upcoming experiments such as NOνA and T2K expect these interactions to be a large portion of the cross section in the energy region in which they are most interested. The use of similar near and far detectors serves to partially cancel detector systematic errors. However, since there are different incoming neutrino spectra at the near and far detectors and these mostly unknown resonance cross sections are energy dependent, the neutrino cross section errors do **not** cancel and there is a vital need for the systematic and detailed studies MINERνA can provide.

High statistics muon neutrino disappearance experiments are particularly sensitive to the hadronic final state, in particular the number, charge, and kinematics of the final state pions. The lack of knowledge of these final states contributes to an uncertainty in the total hadronic energy, and therefore to the estimate of the incident neutrino energy and the parameter Δm^2. For electron neutrino appearance experiments, constraints on the cross sections of neutral current and charged current single π^0 production are needed. In the expected signal region, the former could enter as background from higher energy resonance and DIS interactions, while the latter would primarily be high ν resonance events. In both cases, some kinematic combinations of the resulting decay photons could be indistinguishable from charged current electron neutrino interactions.

For MINERνA the combination of cross section, nuclear effects, and proton and pion final state interaction measurements will require the tracking and calorimetric abilities of a fully active, fine-grained detector.

2.2.2 Cross Section Models and Existing Data

Scattering of electrons and neutrinos off nucleons with hadronic invariant mass $W < 2$ GeV is dominated by resonance excitation. A complete description of the resonance region would require a complete map of all resonances and the non-resonant processes that contribute. About two dozen resonances are known and each has form factors. Even with much larger statistical accuracy, interpretations of electron scattering data have not reached this laudable goal. The lowest energy states are most easily separated; the most prominent resonance is the $P_{33}(1232)$ (often called the Delta), and most calculations also include the $S_{11}(1535)$, $P_{11}(1440)$, and $D_{13}(1520)$.

Using the Rein and Sehgal formalism, some simulation authors [9] include up to 18 resonances in neutrino simulations. In electro-production, the Delta is most important at low W and the the magnetic dipole term in the cross section dominates. This form factor has a particularly rapid Q^2 falloff (more steep than the nucleon dipole form factor) and emphasizes the C_3^V vector form factor. For neutrino induced resonances, the contribution of C_5^A (due to the axial form factors) is important and these two may be sufficient for a qualitative picture. The axial form factor is determined by the PCAC condition, and is also steeper than the dipole shape. The Delta has received a lot of attention in the medium energy community. Current wisdom is that the mesonic cloud surrounding the quark core dominates the low Q^2 response. That model has been extended to neutrino-nucleon excitation of $P_{33}(1232)$ by Sato, Uno, and Lee [2, 4]. Another model has been developed by Paschos, Sakuda, and Yu [3] and applied to nuclei. Examples of both models are shown in Figure 1 compared with data from the Brookhaven Deuterium bubble-chamber experiment [5, 6]. In the plot on the right are shown the axial and vector contributions to the total cross section; the latter is well constrained by electron scattering experiments. These models describe existing data through most of the region shown, though that data has large uncertainties and does not provide much constraint. There are also large inconsistencies at very low $Q^2 < 0.2$ (GeV/c)^2. The lack of agreement at very low Q^2 has been seen in various interactions and has important consequences for the estimation of the coherent π^o background [7] for ν_e appearance experiments.

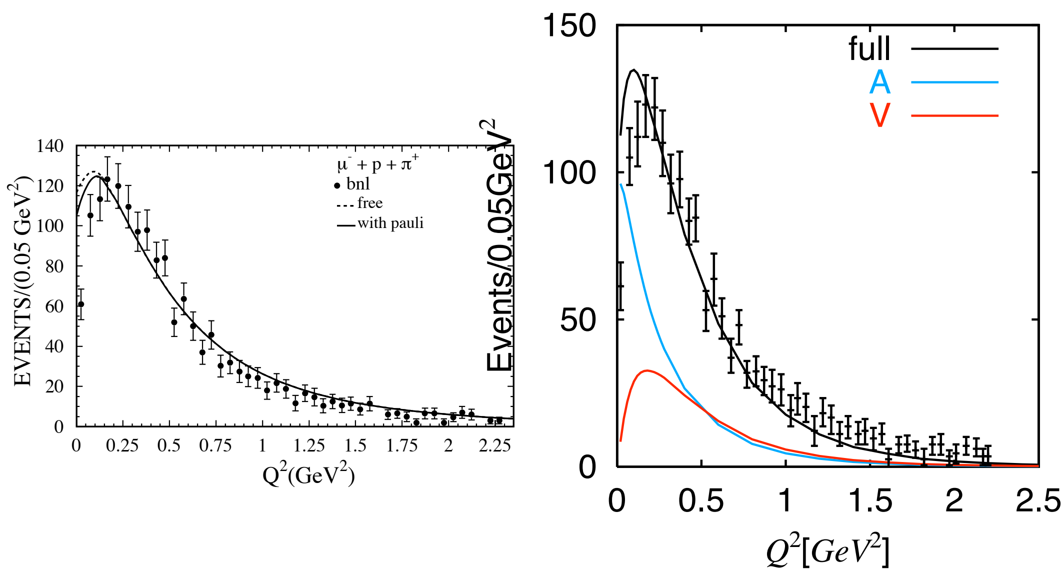

Figure 1: The cross-section $d\sigma/dQ^2$ from BNL compared with fits from Paschos, et al. [3] in the left plot. The full lines are for $M_A = 1.05$ GeV/c^2, the dashed lines have no explicit Pauli blocking included. The plot on the right is from the work of Sato, et al. [4] and shows their calculation compared to the same data, but also breaks down the Axial and Vector contributions to the total cross section.

The Q^2 dependence is determined by these form factors as well as nuclear effects, and in turn determines the outgoing angular distribution of the lepton as well as the hadronic final state particles. One concern, for both resonance and quasi-elastic scattering off nuclei, are nuclear effects (especially Pauli blocking) which certainly play a large role at very low Q^2; this corresponds to more forward going final state leptons, a kinematic region which is difficult to access in electron beam experiments. This uncertain region accounts for a significant fraction of the total cross section. MINERνA with its variety of nuclear targets, can start to disentangle nuclear effects from form factors.

The poor understanding of the resonance cross section also impacts quasi-elastic cross section measurements. Experiments with relatively high thresholds for recoil nucleons and pions, such as Cerenkov detectors or coarse grained tracking detectors will frequently see only the outgoing lepton, and will tag it as a QE candidate. Any measurements of these interactions, or measurements which depend on the kinematic simplicity of a purified QE sample, will benefit from the improved measurement of the resonant background.

There are concerns, even when the outgoing pion can be seen, such as the π^o decay to two photons, or charged pions which are above detection threshold. The kinematics of these pions are often modified as they pass through the nucleus, sometimes even being completely absorbed. There will be a reduction of approximately 30% of pions with the same charge as the exchange current (π^+ for neutrino CC interactions) produced in a light target such as C or O. This is due to a combination of charge exchange (to π^o or π^-, for example) or absorption. These final state nuclear effects will change the visible energy, requiring corrections to estimate the true neutrino energy, the quasi-elastic cross section, or where π^o backgrounds are important such as ν_e searches. Again, MINERνA 's integral nuclear targets and low tracking thresholds are designed to isolate exclusive single pion production and to disentangle these nuclear effects.

2.2.3 MINERνA performance

MINERνA will be able to improve the above situation with precision measurements of the total resonance cross sections, of the $d\sigma/dQ^2$ and $d\sigma/dW$ differential cross sections, and measure exclusive final states on a variety of nuclei to constrain the form factors and final state interaction models. One major goal is to provide a characterization of the final states and the energy dependence of the cross sections for the many contributing processes (pion production and nucleon knockout). With a fully active detector, MINERνA will be able to measure almost all final states. The angular distributions can be determined in most cases. The second goal is to study the details in special cases when individual resonances can be isolated. Building on experiences with electron scattering experiments, we will be able to isolate $P_{33}(1232)$ and $S_{11}(1535)$ by taking advantage of their decay processes.

Unlike inclusive charged lepton scattering (e,e'), measurements of neutrino inclusive scattering with wide-band neutrino beams can not rely solely on the outgoing lepton kinematics, since the incident neutrino's exact energy is not *a priori* known. Reconstruction of inclusive resonance production requires the measurement of W; for the dominant Delta resonance this will be at 1.232 GeV. For charged current interactions this is accomplished by measuring the lepton energy and angle (which is easy for muons) and also either the hadronic energy or its angle. Measuring these also gives estimates for Q^2 and E_ν.

The hadronic energy can be estimated by tracking and identifying every particle emerging from an interaction vertex, or by summing up the dE/dx energy deposited by all the reaction products other than the muon. Because the primary vertex multiplicities for resonance production will usually be low, a single pion and recoil nucleon, tracking (momentum from range) will be the most important technique. However, the pions have a non-negligible probability to decay or interact before stopping, and MINERνA 's calorimetric abilities will be required to reduce biases and to accurately get the inclusive cross sections. The correlation between the reconstructed and true E_ν is shown in Fig. 2.

When the kinematics of resonance events are reconstructed using E_h and an assumed muon momentum resolution $\delta P/P$ of 9%, we obtain the correlation of the reconstructed and true W and Q^2

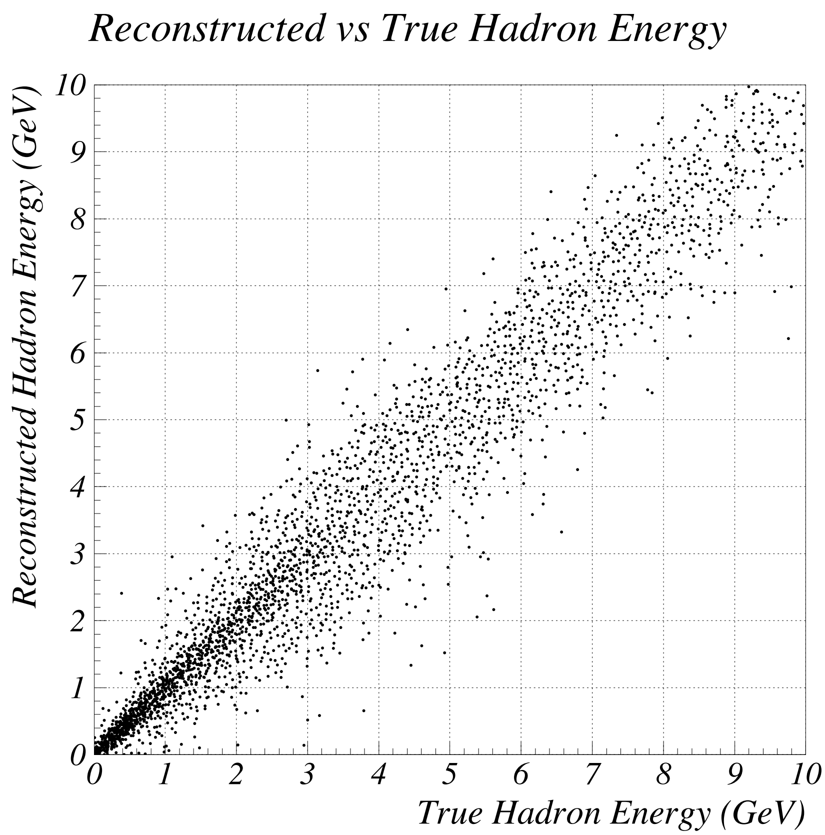

Figure 2: Correlation between true and reconstructed hadron energy.

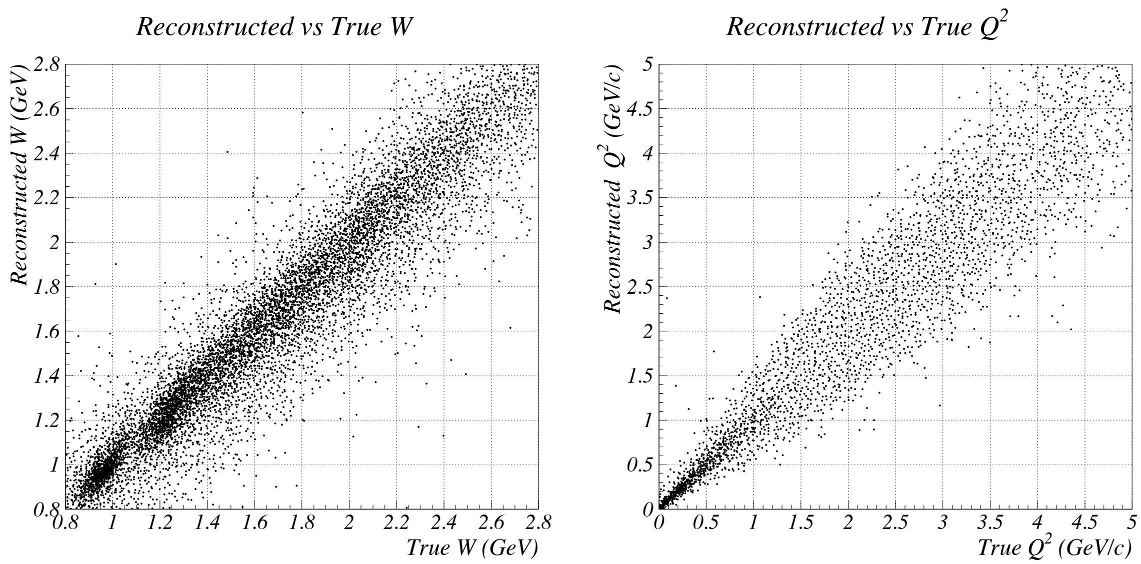

Figure 3: Correlation between true and reconstructed W (left) and Q^2 (right).

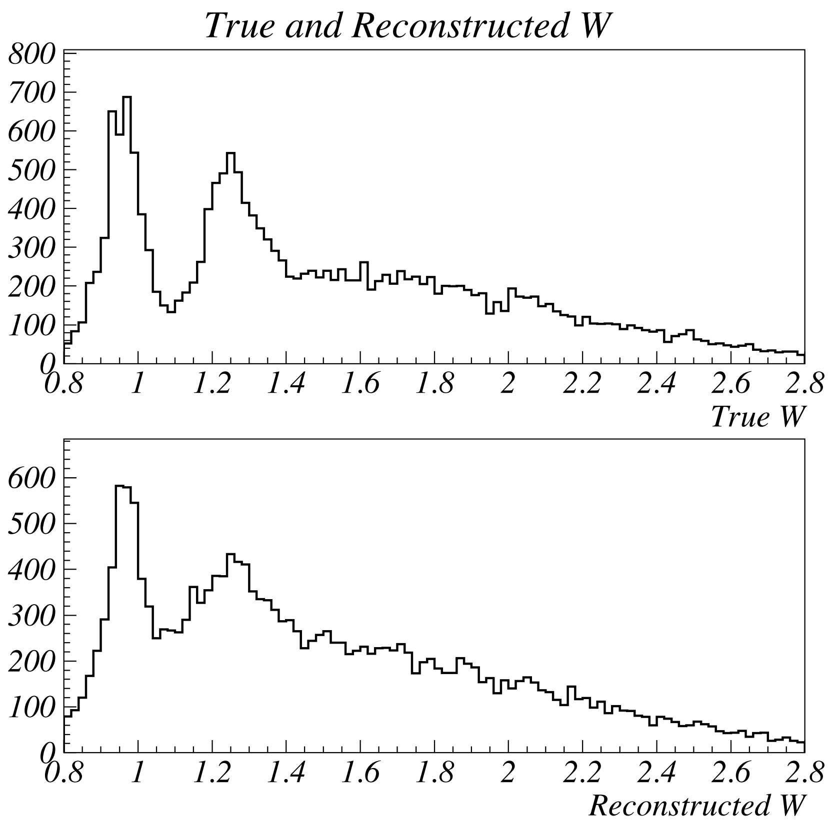

Figure 4: Top: true W distribution for resonant events with $Q^2 < 1$ (GeV/c)^2. Bottom: reconstructed W distribution for the same Q^2 range.

shown in Fig 3. The W resolution is around 100 MeV in the region of the Delta, and the Q^2 resolution is slightly better than 0.2 (GeV/c)^2. Even with this smearing, the Delta peak is still visible in the W spectrum in both Fig. 3 and also in the histogram in Fig. 4. Note, the smearing is largely due to detector effects, but there is a smaller, but still significant smearing due to nucleon Fermi motion for interactions taking place in carbon.

2.2.4 Identifying specific final states

Previous neutrino studies have focused on charged particles because they are easier to track. However, the best physics interest in the resonance region might come from neutral particles such as π^0, η, and ω. That is because there is a preponderance of strongly excited baryon resonances close to their thresholds. The strong coupling of $\pi^0 p$ to the $\Delta(1232)$ resonance is well-known and the strong ηp coupling to $S_{11}(1535)$ is now also very well established. There is also a resonance at the ωN threshold ($P_{13}(1720)$), but its properties are not well-determined. Isolation of either of the higher mass states would be a major accomplishment. Then, it becomes possible for ν beams to add to the knowledge of these states.

Each of these mesons must be detected through decays. The π^0 decays almost solely to $\gamma\gamma$; that is also the largest decay branch for η. The signature would be clean: two photons of half the meson mass at large opening angle. The next largest decays for η are 3 pions, with charged ($\pi^+\pi^-\pi^0$) and neutral modes ($3\pi^0$) both prominent. The primary decay of ω is also to $\pi^+\pi^-\pi^0$. This mode should also be seen in the MINERνA detector because low energy particles will be contained very well. In each case, the invariant mass of a proton+meson pair could be constrained to be near the mass of the appropriate resonance as an additional way to suppress background. Studies of these modes are just beginning.

2.2.5 Error budget

The significant errors to some of the above analyses have been estimated; what is important depends on the measurement. For absolute cross section measurements, we expect a 5% absolute error when the MIPP hadron production results are incorporated into the NuMI beam flux. This is certainly an improvement over the previous bubble chamber results where $> 20\%$ errors are reported (for a recent discussion see [8]). At this level, uncertainties in background subtraction may be comparable. For relative cross sections, the relative flux error between neighboring energy bins will be 2%, and those measurements will be dominated by resolution and calibration errors.

For the analysis of the shape of Q^2 or other distributions, such as in Fig. 1, the largest error will likely be from bias in the energy reconstruction. For example, a 2% uncorrectable bias in the muon momentum translates to an uncertainty in the shape of the Q^2 distribution that is about half as large as the apparent discrepancy in those plots, when you consider MINERνA 's statistical error will be negligible for those distributions.

The extraction of pure nuclear effects from comparisons between the MINERνA nuclear targets, including the very low Q^2 region and the rescattering and absorption of final state pions, will probably be statistics limited. Because the detector surrounding the nuclear targets are the same, systematic uncertainties in the relative measurements will partially cancel. Thus, the limiting factor will be the maximum practical size for these targets.

2.2.6 Conclusion

MINERνA will significantly improve current measurements of resonance production of pions in neutrino interactions due to the large event samples, variety of nuclear targets, low detection thresholds, and excellent tracking and calorimetry. These measurements will be able to constrain the total cross section, relative cross sections, and the shape of the Q^2 distributions, and allow the first direct comparisons of neutrino interactions on different nuclei. These physics goals are consistent with the expected systematic and statistical errors. Better data on these processes will be of vital importance to current and future oscillation experiments as well as nucleon decay experiments. They will also lead to better understanding of the axial form factors of the nucleon and the effects of the nuclear medium.

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